

# First results from the VIMOS-IFU survey of gravitationally lensing clusters at $z \sim 0.2$

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**Summary.** We present the on-going observational program of a VIMOS Integral Field Unit survey of the central regions of massive, gravitational lensing galaxy clusters at redshift  $z \simeq 0.2$ . We have observed six clusters using the low-resolution blue grism ( $R \simeq 200$ ), and the spectroscopic survey is complemented by a wealth of photometric data, including *Hubble Space Telescope* optical data and near infrared VLT data. The principal scientific aims of this project are: the study of the high- $z$  lensed galaxies, the transformation and evolution of galaxies in cluster cores and the use of multiple images to constrain cosmography. We briefly report here on the first results from this project on the clusters Abell 2667 and Abell 68.

## 1 Introduction

Because of their intense gravitational field, massive (i.e.,  $M > 10^{14} M_{\odot}$ ) clusters of galaxies act as Gravitational Telescopes (GTs) and are therefore an important tool to investigate the high-redshift Universe (see, e.g., [1]). In order to fully exploit the scientific potential of the GTs we have started an extensive integral field spectroscopy (IFS) survey of massive galaxy clusters. Targets have been selected among well-known gravitational lensing clusters between redshift  $\sim 0.2$  and  $0.3$ , for which complementary *Hubble Space Telescope* (HST) data are available. All the clusters are X-ray bright sources. Our sample partially overlaps with the one analyzed in [12].

IFS is the ideal tool in order to obtain spatially complete spectroscopic information of compact sky regions such as cluster cores. Moreover, cluster cores are the regions where strong lensing phenomena are observed (i.e., giant arcs and multiply imaged sources): for clusters in our sample, strongly lensed galaxies are within  $\theta \simeq 1$  arcmin from the cluster center.

VIMOS-IFU [8] is thus the natural choice for such observational program, since, at present, it provides the largest f.o.v. for among integral field spectrographs mounted on the 8-10m telescopes.

All the clusters in our sample have been observed using the low-resolution blue (LR-B) grism, with a spectral resolution  $R \sim 200$ . Taking into account

the lower efficiency at the end of the spectra and the zero order contaminations, the final useful spectral range is limited between  $\simeq 3900 \text{ \AA}$  and  $6800 \text{ \AA}$ . This spectral range is suitable both for detecting high-redshift source (e.g., Ly $\alpha$  emitters in the redshift range  $2.2 < z < 5.5$  or [OII] emitters out to  $z \sim 0.8$ ) and to sample the rest-frame  $4000 \text{ \AA}$  break for the cluster galaxy population. With a fiber size  $0.66 \text{ arcsec}$ , the IFU f.o.v. covers a contiguous region of  $54 \times 54 \text{ arcsec}^2$ , sampled by 6400 fibers.

A subset of the clusters in the sample has also been observed using a higher resolution grism ( $R \simeq 3000$ ) covering the  $\lambda = 6300 - 8600 \text{ \AA}$  range. These observations are useful to probe higher redshift Ly $\alpha$  emitters at  $4.2 < z < 6.1$  or [OII] emitters at  $0.7 < z < 1.3$ .

Observations have been completed (see Table 1 in [13]), and data reduction is now in progress. The data reduction process has been described in [2], and [15] gives details about VIPGI, the VIMOS dedicated pipeline. Furthermore, we have developed a SExtractor-based tool to help in object detection and spectra extraction from the fully reduced datacube [5].

Altogether, our IFS survey covers a region of about 9 square arcmin in the central regions of six massive clusters.

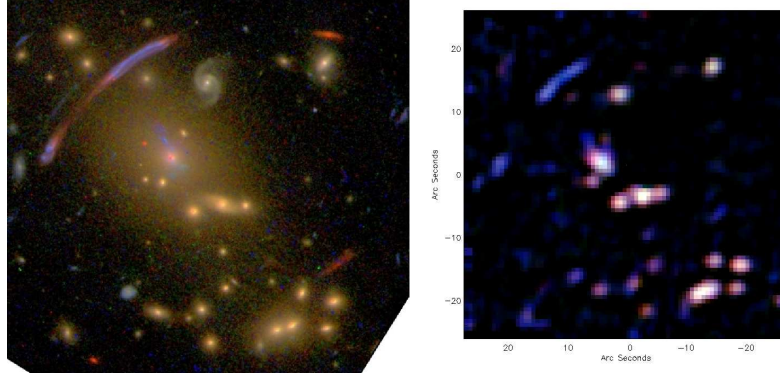
Hereafter, we briefly report on the first results from this project: the mass distribution in Abell 2667 in Sect. 2, the properties of a magnified high- $z$  source in Abell 68 in Sect. 3 and an investigation of cluster galaxies in Sect. 4. We refer to the presentation by G. Soucail [13] for a detailed discussion of the cosmography aspect of the project.

## 2 Mass distribution model: A2667

Wide field IFS of the cluster central regions provides simultaneously spectroscopic redshifts of both the cluster members and the images of the gravitationally lensed sources, thus allowing a direct comparison of the strong lensing analysis with the dynamical one. Abell 2667 (hereafter, A2667) is a very remarkable galaxy cluster at  $z = 0.233$ : it is among the top 5% most luminous X-ray clusters (at its redshift), and shows one of the brightest gravitational arc in the sky (Fig. 1).

A2667 has been observed with VIMOS-IFU during two separate nights (june 2003), with a total of 4 pointings of 2400s each, centered on the cD galaxy, using the LR-B grism (see [2] for details). A small offset of about 2 arcsec was performed between the first and last two pointings. Therefore, as consequence of the small number of pointings, a not optimal dithering strategy and observations carried on two separate nights, the sky subtraction has not been optimal.

Nevertheless, we have obtained the spectroscopic measurements of the redshift for 34 sources in the central  $54 \times 54 \text{ arcsec}^2$  region of the cluster, cor-



**Fig. 1.** Three color images of the inner arcmin square in the cluster A2667. Left panel: image created from the HST-WFPC2 data, filters B<sub>450</sub>, V<sub>606</sub> and I<sub>814</sub>. Right panel: from the VIMOS-IFU datacube, using slices centered at  $\lambda = 4600, 5200$  and  $6000 \text{ \AA}$ .

responding to a box of  $200 \times 200 h_{70}^{-2} \text{ kpc}^2$  at the cluster redshift<sup>6</sup>. It includes in particular: 22 cluster members (i.e., all the cluster members brighter than  $V_{606} = 23.2$ , AB system) and the three separate images of the giant gravitational arc ( $z = 1.0334$ ).

Using the spectroscopic redshift and the multiple images identified on the HST-WFPC2 image, we have built a strong lensing model and performed a dynamical analysis of the cluster core, both resulting in mass of  $\simeq 7.2 \times 10^{13} M_{\odot}$  within the central  $110 h_{70}^{-1} \text{ kpc}$ , and a velocity dispersion of  $\simeq 950 \text{ km s}^{-1}$ , close to the value derived from the X-ray temperature (assuming that the cluster follows the  $\sigma - T$  relation).

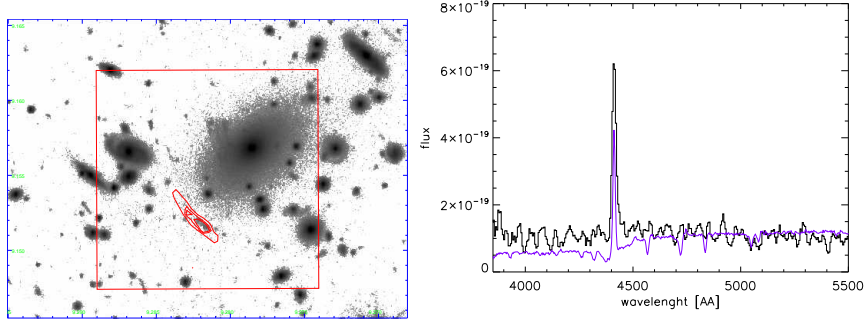
Such agreement supports the idea that A2667 cluster core is in a relaxed dynamical state, as expected from its regular X-ray morphology (Rizza et al. 1998). Therefore, A2667 core appears to be dynamically evolved, in contrast with the large fraction ( $70 \pm 20 \%$ ) of unrelaxed clusters with similar X-ray luminosity at similar redshift [12].

### 3 Physical properties of a unusual lensed high- $z$ source

The combination of IFS and the large magnification provided from strong lensing gives a unique opportunity to study in detail (i.e., the spatially resolved) the spectral properties of intrinsically low-luminosity source in the high- $z$  Universe, (see, for instance, [14]).

VIMOS-IFU observation of the core of the galaxy cluster Abell 68 ( $z = 0.255$ ) has revealed a surprisingly extended Ly $\alpha$  emission around a previously

<sup>6</sup>We use a cosmological model with  $\Omega_{\Lambda} = 0.7$  and  $\Omega_m = 0.3$



**Fig. 2.** Galaxy cluster A68. Left panel: HST R<sub>707</sub>-band image of the cluster, with the VIMOS-IFU f.o.v. and the lensed source C4. Note its wider extension as detected by means of the IFS. Right panel: one-dimensional VIMOS spectrum of the arc compared with a template of a  $z = 3$  Lyman-break galaxy from [11].

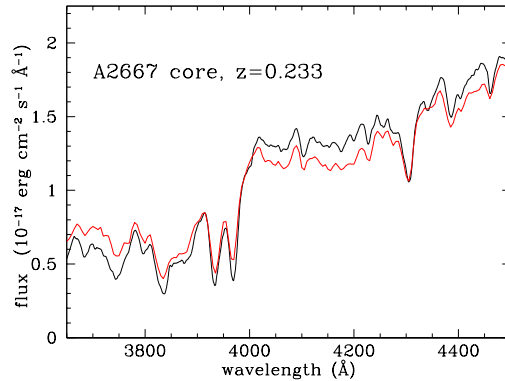
known gravitationally lensed source [3] (denoted as C4 in [12],  $z = 2.625$ ). As shown in Fig. 2, the arc is seen to be  $\sim 4$  arcsec in length on the HST-WFPC2 image (filter R<sub>707</sub>, exposure time 7.5 ks). But in our shallow IFU pointing (4.8 ks), the arc is seen to be much more extended [3], reaching a maximal elongation of  $\simeq 10.8$  arcsec. The emission line is not resolved in the IFU data, and its equivalent width is about 140 Å, and remains constant within the errors along the source length.

According to the strong lensing model, the source is single imaged and its magnification is  $\mu \sim 35$ : the intrinsic shape of the Lyman- $\alpha$  emitting region has a disk-like appearance (see [3]) with a maximum extension of  $\simeq 10$  kpc. It is therefore about 10 times smaller than Ly $\alpha$  blobs (see, for instance, [9]) but much bigger than a typical galaxy at  $z \sim 2.5$ . One possibility is that we are observing a  $\sim L_*$  galaxy undergoing a strong star-formation event, with negligible dust-obscuration.

## 4 Cluster galaxies investigations

The central region of rich galaxy clusters at intermediate redshift is expected to host an old and red galaxy population, in great majority composed of early-type galaxies, see e.g. [7], which at a redshift of  $z < 1$  is passively evolving, with very low levels of star-formation activity.

Recently, [4] have shown that *composite cluster spectra*, built from the light-weighted combination of all the cluster members long-slit spectra, are a useful tool to provide insights in the properties of the cluster population. In this respect, IFS offer a unique possibility to build cluster composite spectra in unbiased way, since, for a given field of view, all clusters members are observed (without any *a priori* selection) and, for each galaxy, all the light



**Fig. 3.** Composite spectrum of the galaxy population in the core of the cluster A2667 (black line), compared with the template spectrum of  $z = 0$  early-type galaxies (red) from [6]. The contribution of the cD galaxy is excluded, since it appears to host an AGN.

is collected (therefore avoiding the possibility that for larger galaxies some flux contribution might be missed due to the specific orientation of the slit). Preliminary work (see Fig. 3) appears to confirm that the galaxy population in the very central region of A2667 is dominated by an evolved and passively aging stellar population. We plan to build composite spectra for all the clusters, and to exploit the recent *Spitzer* mid-infrared observations to complement this result and provide quantitative upper limits on the hidden star-formation in the cluster cores.

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